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Conceptual Design of Beryllium Targets for the Generation of Neutron Beams for Radiation Therapy by the (p,n) Reaction.*

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Introduction

The current preference in the production of neutron beams for radiation therapy leans toward the use of high energy protons incident on beryllium targets. This is partly due to the fact that, for equally massive cyclotrons, transport, and delivery systems, attainable proton energies produce more penetrating beams and greater dose rates per unit current than corresponding attainable deuteron energies.[1,2] This follows from $E_p = 2E_d$ for $p_p = p_d$, where $E_{p,d}$ and $p_{p,d}$ are the energy and momentum of the proton and deuteron beams when the accelerator and transport system elements have been designed for operation at nearly equal magnetic fields.

The choice of beryllium as target material was not immediately obvious since lithium has a lower atomic number and might have had a larger neutron yield. However, experiments using 35 and 65 MeV protons in conjunction with the development of the Fermilab neutron therapy beam[1] showed that dose per unit charge was practically the same for "thick" lithium and beryllium targets.

In the above experiment, it was also shown that for an incident proton beam of constant energy and current, the dose

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rate decreased slowly as the target was made thinner. With available data[1] the dose rate may be shown to be related to the proton energies by

$$\dot{D} = K E_i^{3.2} \left[1 - \left(\frac{E_i - e_t}{E_i} \right)^{3.2} \right] I$$

where $\dot{D}$ = dose rate,

K = geometric factor involving target to skin distance, collimator size, and appropriate conversion factor,

E_i = incident proton energy,

e_t = energy lost by protons which have undergone only elastic scattering in the target, and

I = beam current.

This work evolved from previous work[1] and it was originally undertaken when one of the authors was briefly involved in the planning of a hospital-based neutron therapy facility for Chicago.

Target Design Considerations

In designing a target for generation of neutron beams, some of the performance parameters that must be taken into consideration are:

1) neutron dose rate at required treatment distance
2) skin sparing
3) depth dose distribution in tissue
4) sharply defined beam penumbra
5) target cooling and reliability, and
6) remanent radioactivity in the vicinity of the target,

all subject to available proton energy and beam current.

The neutron dose rate is intimately related to available proton beam energies and currents as well as to acceptable power densities in the target structure. Cyclotrons now being offered commercially[3,4] have energies in the 40 - 45 MeV range and currents in the 50 - 200 μA range. Therefore, the present discussion is limited by these restrictions.

It is argued in the appendix that for maximum values of (2) and (3), the target should be thin, i.e., the protons should not stop in it. However, some considerations show that very thin targets are impractical. These considerations relate to presently available beam currents, and to target beam power densities, once the power density, i.e., watts/cm^2, in the target backing material approaches that in the beryllium itself. The neutron production in the proton backstop is not a minor consideration either.

Values of 2.5 to 3.2 kW/cm^2 have been found satisfactory for long life of water-cooled Be-targets.[5,6] Beryllium target reliability involves the avoidance of high power densities in the target that will destroy it by melting as well as the problem of target fatigue and shattering. Thus, a syntered beryllium target is preferable to a pure metallic one. Typically, such materials as HP-10 have Be content of over 99% of the mass, the rest being mostly BeO, Fe, C, Al, Mg, and Si.[7]

Targets are preferably cooled through their downstream surfaces. Then, cooling and removal of the unwanted proton beam power as well as vacuum sealing take place in that region. Spreading of the proton beam upstream from the target to reduce target power density must be balanced against the degradation of the sharpness of the neutron beam penumbra.

The protons exiting the Be-target will produce neutrons in the backstopping material. Thus, the selection of this material will cause significant variations in the level of parasitic neutron generation and remanent radioactivity. We propose the use of a thick water backstop. This choice leads to minimum neutron production[8] and some hardening of the neutron beam by removal of low energy neutrons. However, it also increases the formation of radioactive nuclides in the water itself and its dissociation into H_2 and O_2 by radiolysis.

Various choices of target thickness for an incident proton beam having an energy of 45 MeV are presented in Table I. Column 1 gives the energy loss of protons by ionization only as they cross the beryllium thickness shown in column 2. Column 3 gives the relative dose rates at constant geometry and constant beam current for the different targets. Columns 4 and 5 show the relative beam currents required to maintain a constant dose rate and the corresponding beam power dissipation in the targets. Columns 6 and 7 show the relative beam currents which could be tolerated at constant power dissipation in the targets and the consequent relative dose rates. It is apparent that for constant target power dissipation substantial increases in dose rate may be achieved using thinner targets, provided that the higher beam currents can be obtained.

One Target Design Example

Consider a Be target thick enough to remove 15 MeV from a 45 MeV incident proton beam. The outgoing protons would have an energy of 30 MeV. The backing of the Be-target should be a high thermal conductivity metal such as copper. Let this backing be copper of 0.25 mm thick. Then, the protons outgoing from the copper would have an energy of approximately 28 MeV which could be stopped by about 8 mm of water.

Assume a dose rate of 60 rad/min at 150 cm SSD is desired from this target design using a 10 x 10 cm^2 beam. This would require a beam current of 60 μA,[2] leading to a target power dissipation of 60 μA x (15 MeV target + 2 MeV backing foil) = 1.02 kW. Assuming a beam diameter of 0.7 cm, this leads to a safe power density of 2.6 kW/cm^2. By comparison, a thick target would have required only 43 μA, but it would have had a power dissipation of 1.94 kW, or about 4.9 kW/cm^2 at the above diameter, higher than the accepted safe limits. A larger beam diameter would then be required, degrading the sharpness of the neutron beam.

Conclusions

It is argued that a target may be easily designed for neutron beam production that allows adequate dose rates at a satisfactory SSD, well within available beam currents and within acceptable target power densities while improving the beam penetration. The paper that follows presents results of measurements using a 42 MeV proton beam incident on Be-targets of various thicknesses. These results tend to support the arguments presented in this paper.

TABLE I

Comparison of properties for various Be-target thicknesses for 45 MeV proton beams

1	2	3	4	5	6	7
Target thickness at 45 MeV (e_t) MeV	Target thickness (Beryllium) cm	Current = Constant	Dose Rate = Constant		Target Power = Constant	
		Relative Dose Rate*	Relative Beam Current (I)	Relative Target Power **	Relative Beam Current	Relative Dose Rate
45	1.224	1.000	1.000	1.000	1.000	1.000
25	.924	.925	1.08	.600	1.80	1.66
20	.802	.848	1.18	.524	2.25	1.91
15	.637	.727	1.38	.459	3.00	2.18
10	.447	.553	1.81	.402	4.50	2.49
5	.235	.314	3.18	.354	9.00	2.38

$$* \quad \dot{D} \propto \left[1-\left(\frac{45-e_t}{45}\right)^{3.2}\right]$$

** Target Power = $I \cdot e_t$

APPENDIX

Effects of Be-target thickness on skin sparing and depth dose distributions at constant incident proton energy.

Skin sparing. To a first approximation the depth for D_{max} is not affected by the thickness of the target. This depth is primarily determined by the maximum energy of the recoil protons in the tissue which depends on the maximum neutron energy. However, the transition from the entrance dose to D_{max} will be affected by the spectrum of lower energy neutrons because they will produce correspondingly more protons of lower energy and range. These lower energy protons will be absorbed between the skin and the depth of D_{max}. This effect is emphasized by the (n,p) cross-section in tissue which increases as the neutron energy decreases.[9] This means that the lower energy neutrons present in the thick target spectrum should reduce skin sparing. A monochromatic neutron beam would produce the maximum skin sparing for an essentially constant depth of D_{max}. A very thin Be-target produces a neutron energy spectrum peaking near the incident energy of the proton plus a small continuous distribution and a rising spectrum at the low energies.[10, 11, 12] Most of the energy is carried by the neutrons in the peak. This is the closest neutron energy spectrum to a monochromatic beam that can be made with protons on a Be-target. Thus, one may conclude that at constant proton energy, as the target thickness is decreased, the depth for D_{max} remains essentially constant but the skin sparing improves.

Central Axis Depth Dose. The discussion that follows is based on the atomic compositions of ICRU-muscle.[13] This composition has the following atomic ratios:

H:C:O:N::10.1:1.02:4.56:0.25.

In the energy range 1 - 45 MeV, the total scattering cross-section for neutrons in hydrogen decreases monotonically with increasing energy.[9] For carbon and oxygen the total cross-sections have complex behaviour but generally decrease between 1 and 10 MeV, slightly increase between 10 and 20 MeV and, from 20 MeV on, continuously decrease as the energy increases to values beyond 100 MeV. These cross-sections then lead to the prediction that the neutron mean free path will increase monotonically with increasing neutron energy. Even in the 10 - 20 MeV region, where the carbon and oxygen cross-sections increase slightly (1.2 to 1.5 b and 1.2 to 1.7 b, respectively), the decrease in the hydrogen cross-section (.9 to .5b) strongly offsets this decrease. Not only do more energetic neutrons have longer mean free paths, but the kerma due to their interactions also increases monotonically with energy.

Hence, the thin target distribution would maximize the production of neutrons with the longest mean free path and the greatest kerma, thus increasing the depth at which the dose decreases to half the value of D_{max}.

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